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DISCOVERY OF FIVE BINARY RADIO PULSARS

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Accepted for publication by The Astrophysical Journal Letters, December 7, 2000

ABSTRACT

We report on five binary pulsars discovered in the Parkes multibeam Galactic plane survey. All of the pulsars are old, with characteristic ages 1–11×10^9 yr, and have relatively small inferred magnetic fields, 5–90×10^8 G. The orbital periods range from 1.3 to 15 days. As a group these objects differ from the usual low-mass binary pulsars (LMBPs): their spin periods of 9–88 ms are relatively long; their companion masses, 0.2–1.1 $M_\odot$, are, in at least some cases, suggestive of CO or more massive white dwarfs; and some of the orbital eccentricities, $10^{-5} \lesssim e \lesssim 0.002$, are unexpectedly large. We argue that these observed characteristics reflect binary evolution that is significantly different from that of LMBPs. We also note that intermediate-mass binary pulsars apparently have a smaller scale-height than LMBPs.

Subject headings: Binaries: general — pulsars: individual (PSR J1232−6501, PSR J1435−6100, PSR J1454−5846, PSR J1810−2005, PSR J1904+0412)

1. INTRODUCTION

Most of the ~ 40 binary pulsars known in the disk of the Galaxy are millisecond pulsars with weak magnetic fields ($B \sim 10^8$ G), spin periods $2 < P < 15$ ms, and in nearly circular orbits with companions of mass $0.15 \lesssim m_2 \lesssim 0.4\,M_\odot$, presumably He white dwarfs (WDs), some of which have been detected optically. These are the low-mass binary pulsars (LMBPs), and their formation mechanism is well understood. After a neutron star spins down to long periods and a low-mass companion evolves off the main sequence, a long phase of stable mass-transfer ensues, during which the system may be detectable as a low-mass X-ray binary (LMXB; see Verbunt 1993 for a review). Eventually the orbit is circularized (Phinney 1992), the pulsar spins up, its magnetic field is somehow quenched (e.g., Romani 1990), and a long-lived 'recycled' radio millisecond pulsar emerges. Despite some uncertainties, it appears that the birth-rates of LMXBs and LMBPs are comparable (Lorimer 2000), and this evolutionary model successfully accounts for many properties of LMBPs. However, it should be noted that 20% of millisecond pulsars are isolated, and it is not clear how they have lost their presumed past companions.

A small but growing group of binary pulsars consists of objects with $15 < P < 200$ ms, intermediate-mass companions ($m_2 \gtrsim 0.5\,M_\odot$, likely CO or heavier WDs), and orbital eccentricities in some cases much larger than their LMBP counterparts. These are the intermediate-mass binary pulsars (IMBPs), and it is not entirely clear how they fit into the evolutionary scheme outlined above. It has been suggested that such systems undergo a period of unstable mass-transfer and common-envelope (CE) evolution (van den Heuvel 1994). IMBPs may have more in common with the evolution of high-mass systems that spend part of their lives as high-mass X-ray binaries (HMXBs) and are progenitors to eccentric-orbit double-neutron star binaries, with the difference that they were not sufficiently massive for a second supernova to have occurred.

The vast majority of millisecond pulsars known in the Galactic disk is located within 2 kpc of the Sun. This is due to the loss of sensitivity of most surveys at larger distances, particularly along the Galactic plane. To probe the Galaxy-wide distribution of LMBPs and to learn more about rare species of pulsars it is therefore desirable to search the distant Galactic plane with improved sensitivity.

The Parkes multibeam survey (Lyne et al. 2000; Manchester et al. 2001) covers a region of the inner Galactic plane ($|b| < 5°$, $-100° < l < 50°$) with sensitivity far surpassing that of previous pulsar surveys. The main aim of the survey is to find young and distant pulsars, but it retains good sensitivity to fast-spinning pulsars. A radio frequency of 1374 MHz is used, reducing deleterious propagation effects that affect the detectability of distant pulsars at low latitudes. So far, the survey has discovered more than 500 pulsars (Camilo et al. 2000b; Manchester et al. 2000), including binary (Lyne et al. 2000; Kaspi et al. 2000) and young (Camilo et al. 2000a) pulsars.

In this *Letter* we report the discovery of five short-period pulsars in binary systems. They contribute significantly to our understanding of binary pulsar evolution and demographics.

2. OBSERVATIONS AND RESULTS

The survey uses the 13-beam receiver system at the 64-m Parkes telescope in NSW, Australia. Radio noise at a central frequency of 1374 MHz and spanning 288 MHz in bandwidth is filtered in a 96×3-MHz filter bank spectrometer in each of two linear polarizations, in observations lasting 35 min. Signals from complementary polarizations are added, and the 96 volt-

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ages for each beam are sampled every 250 μs, digitized, and written to magnetic tape for off-line analysis. The data are then searched for periodic and dispersed signals using standard techniques (e.g., Manchester et al. 1996).

Pulsars J1435–6100, J1810–2005, J1454–5846, J1232–6501, and J1904+0412 were first detected in data collected on 1997 May 26, August 26, 1998 January 22, 24, and August 12, respectively. Following confirming observations, PSR J1810–2005 has been monitored in a series of timing observations with the 76-m Lovell telescope at Jodrell Bank, UK, while the remaining pulsars have been observed at Parkes.

At Parkes we record data from the central beam in a manner otherwise identical to the survey observations, while tracking each pulsar for about 15 min on each observing day, with the exception that since MJD 51630 we have observed PSR J1435–6100 with a 512×0.5-MHz filter bank and a sampling interval of 125 μs at a central frequency of 1390 MHz. Data are collected on a few days about every two months, coinciding with epochs during which survey observations are in progress. Also, PSR J1904+0412 was observed on a monthly basis with the 305-m Arecibo telescope, from 1999 October through 2000 July, using the Penn State Pulsar Machine, a 128×0.0625 MHz filter bank with 80 μs sampling at a central frequency of 1400 MHz. The data, time-tagged with the start-time of the observations, are de-dispersed and folded at the predicted topocentric pulsar period, forming pulse profiles; and pulse times-of-arrival (TOAs) are measured by cross-correlating these profiles with high signal-to-noise ratio (S/N) templates (Fig. 1), created from the addition of many profiles. Similar procedures are used at Jodrell Bank, with the difference that the data are de-dispersed and folded on-line; also, 32×3-MHz filter banks were used until MJD 51400, and 64×1-MHz filter banks have been used since.

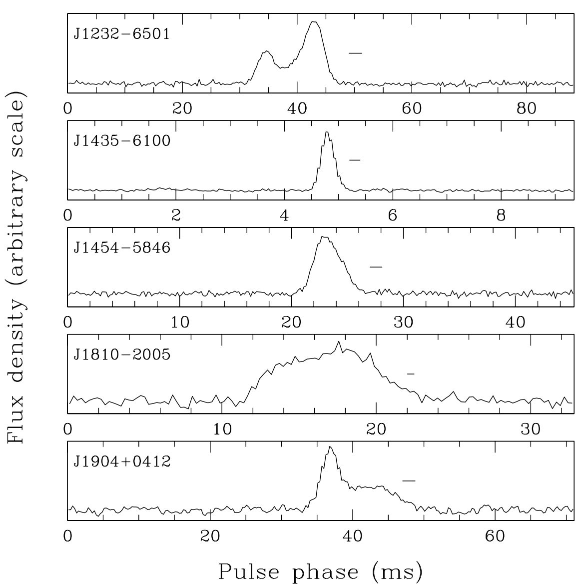

FIG. 1.— Integrated pulse profiles for five pulsars at a frequency of 1374 MHz. The time resolution of each profile is indicated by a horizontal bar. The profiles for PSRs J1232–6501, J1454–5846, and J1904+0412 are the template profiles used to obtain TOAs. That for J1435–6100, at 1390 MHz, is the template for the high-resolution data obtained since MJD 51630, while that for J1810–2005 has time resolution a factor of six better than the template and most of the data used to obtain its timing solution.

We then use the TEMPO timing software[9] to determine celestial coordinates, spin, and orbital parameters for the pulsars. This is done by first converting the measured TOAs to the barycenter using initial estimates of pulsar parameters and the DE200 solar-system ephemeris (Standish 1982), and by minimizing timing residuals with respect to the model parameters. The parameters thus obtained are listed in Table 1, and the corresponding residuals are displayed in Figure 2 as a function of date.

[9]See http://pulsar.princeton.edu/tempo.

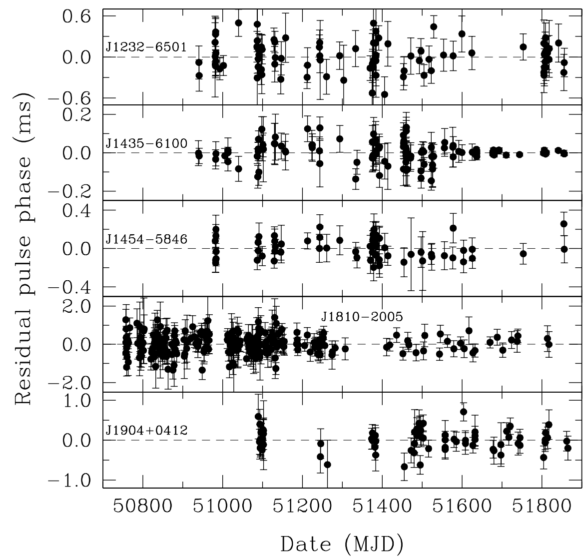

FIG. 2.— Post-fit timing residuals as a function of date for the five binary pulsars. All orbits have been well sampled, and residuals as a function of binary phase are featureless.

The average flux densities listed in Table 1 were estimated by converting the observed S/N to a scale calibrated using stable flux densities known for a group of high-dispersion measure (DM) pulsars. See Manchester et al. (2001) for further details of search and timing procedures.

3. DISCUSSION

3.1. *Evolution of the new systems*

All five of the newly discovered pulsars have low inferred magnetic fields ($B < 10^{10}$ G; Table 1) when compared with the vast majority of known pulsars (see Fig. 3), and all are in circular binary systems. These characteristics indicate that all of the pulsars have interacted with their companions in the past, and have been recycled to some extent. However, their periods and period derivatives (and hence B) are larger than those of most millisecond pulsars, as indicated in the P–$\dot{P}$ diagram of Figure 3: the spin parameters of PSR J1435–6100 place it marginally within the group of LMBPs at the lower left of the diagram, while those for the remaining four pulsars place them squarely amidst the IMBPs and double-neutron star systems.

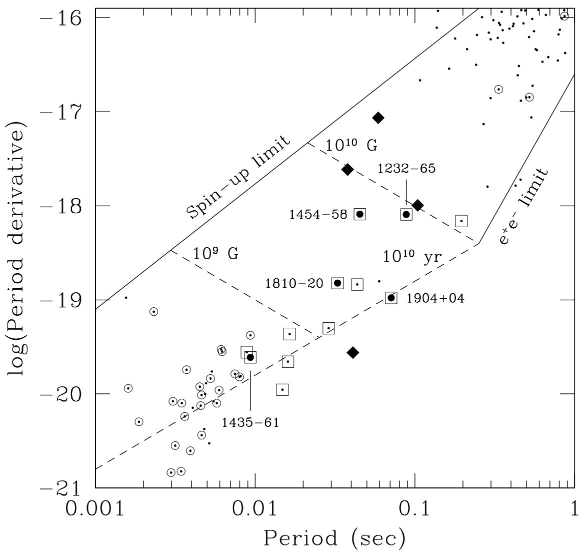

FIG. 3.— Observed period derivative vs. period for the subset of pulsars in the Galactic disk with small period derivatives (more than 1000 known pulsars lie above $\dot{P} > 10^{-16}$). Dots denote isolated pulsars, circles indicate LMBPs, squares represent IMBPs, and diamonds depict high-eccentricity, double-neutron star binaries (see text). Large dots represent the pulsars presented in this paper, labeled by their partial names. Two lines of constant inferred magnetic field strength and a line of characteristic age equal to 10^{10} yr are indicated. Pulsars spun up via mass accretion must reside to the right of the spin-up limit (see Arzoumanian, Cordes, & Wasserman 1999 for a discussion).

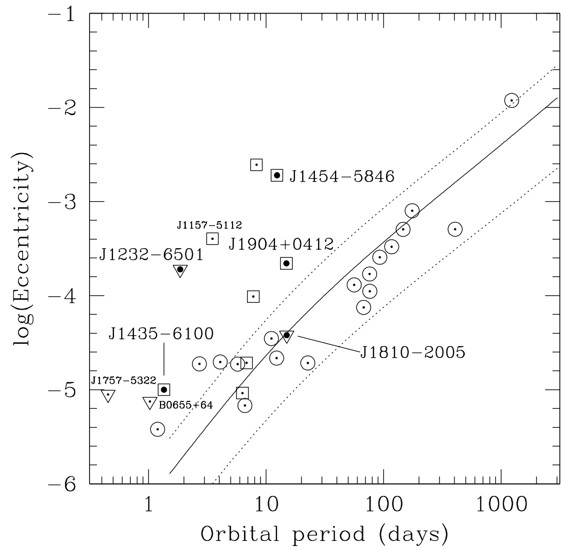

FIG. 4.— Orbital eccentricity vs. period of binary pulsars in the disk of the Galaxy with measured eccentricities $e < 0.1$. Symbols are as in Figure 3, with triangles denoting upper limits. Three IMBPs mentioned in the text are identified in small type. The dotted lines should contain 95% of the eccentricities of the LMBPs (circles), according to the model of Phinney & Kulkarni (1994).

Using the companion masses to attempt a classification of the new systems yields results which are mostly inconsistent with those derived from the spin parameters: PSR J1435–6100 has $m_2 \sim 1.1\,M_\odot$, decidedly not compatible with a LMBP; of the remaining four systems only PSR J1454–5846 ($m_2 \sim 1.1\,M_\odot$) appears to be an IMBP, while the other three have $0.2 \lesssim m_2 \lesssim 0.3\,M_\odot$[10] — on this basis they should be classified as LMBPs, but their periods and magnetic fields are significantly larger than those of any LMBPs with remotely comparable binary periods.

One further piece of useful information is provided by the orbital eccentricities. Phinney (1992) derived a relationship between eccentricity and binary period for LMBPs with $P_b \gtrsim 2$ d that is remarkably consistent with observations. One key ingredient of the theory is that mass transfer to the neutron star via Roche-lobe overflow be stable over the giant phase of evolution of the companion star. The relationship need therefore not hold for IMBPs (Phinney & Kulkarni 1994), and for three of the five IMBPs with measured eccentricities identified so far (Camilo et al. 1996; Tauris & Savonije 1999; Edwards & Bailes 2000) it does not (see Fig. 4).

3.1.1. *Low-mass systems: non-standard evolution?*

Tauris & Savonije (1999) considered the detailed non-conservative evolution of close binary systems with 1–2 $M_\odot$ donor stars and accreting neutron stars, refining the well-known correlation between P_b and m_2 for LMBPs (Joss, Rappaport, & Lewis 1987). The three new low-mass systems (PSRs J1232–6501, J1810–2005, and J1904+0412) follow this relation, considering the uncertainties in m_2.

Tauris, van den Heuvel, & Savonije (2000) then extended this work to intermediate-mass (2–6 $M_\odot$) donor stars. Remarkably, they find that for a certain range of initial orbital periods, such close binaries can survive periods of super-Eddington mass transfer on sub-thermal (few Myr) timescales without experiencing a CE phase. Depending on initial donor mass and orbital period, low-mass systems like the three we have discovered may result (see their Figs. 2 and 4).

How shall we choose between these two alternative scenarios (low- versus intermediate-mass original companions)? Despite their present low-mass companions, the newly discovered systems are unlikely to be standard LMBPs, as already noted, because of their relatively large P and B (PSR J1904+0412 also has too large an eccentricity; Fig. 4). The intermediate-mass donor branch of evolution is therefore more suitable to explain the new systems: the intermediate-mass systems tend to have shorter and less stable periods of accretion, often at much higher rates, leading to a natural explanation for the larger P, B, and (in at least some cases) eccentricities. With this evolutionary path, there is no need for a long-lived X-ray accretion phase. These systems might therefore not be descendants of standard LMXBs, and should be accounted for separately in birth-rate calculations. What the X-ray progenitors of such systems look like is of course an interesting and unresolved question.

3.1.2. *High-mass systems: common-envelope and a puzzle*

As is clear from Figure 4, the eccentricity of PSR J1454–5846 is much higher than predicted by the convective fluctuation–dissipation theory of Phinney (1992). The pulsar therefore has P, B, and eccentricity larger than expected for LMBPs, and $m_2 \sim 1.1\,M_\odot$. We thus confidently classify it as an IMBP with a presumed O-Ne-Mg WD companion. It is likely to have undergone CE evolution and spiraled-in to its present P_b = 12.4 d from an initial period of several hundred days, with a companion of original mass 5–7 $M_\odot$

[10]These estimates of m_2 assume m_1 = 1.35 $M_\odot$ (Thorsett & Chakrabarty 1999) and $i = 60°$; it is unlikely that more than one of the three systems is sufficiently face-on so as to have a $\gtrsim 0.4\,M_\odot$ CO WD companion.

(Dewi & Tauris 2000; Tauris, van den Heuvel, & Savonije 2000). Edwards & Bailes (2000) recently reported the discovery of PSR J1157–5112, a system broadly comparable to PSR J1454–5846, albeit with P_b = 3.5 d and possibly a somewhat larger companion mass.

The pulsar J1435–6100 is likely to have a massive ($m_2 \gtrsim 1\,M_\odot$) O-Ne-Mg WD companion, like PSR J1454–5846. It must have started with a very large orbital period so as not to coalesce during the CE/spiral-in phase, and ended with P_b = 1.35 d, much smaller than P_b = 12.4 d for PSR J1454–5846. A difficulty with understanding PSR J1435–6100 lies in its spin parameters: they are closer to those of LMBPs than IMBPs (see Fig. 3). In other words, despite a presumed short-lived ($\sim 10^4$ yr) mass transfer phase in a CE (and hence very little accretion), the pulsar's magnetic field was somehow quenched to a very low value (5×10^8 G), while it was spun up to a fast initial rate ($P_i \lesssim 9$ ms). Compare its parameters with those of the IMBP B0655+64: P_b = 1.3 vs. 1.0 d; $m_2 \sim 1.1$ vs. $0.8\,M_\odot$; both with similar eccentricities, and likely products of CE evolution. While the orbital parameters are thus fairly similar, the spin parameters are the most different within IMBPs: both B and the present-day period of PSR B0655+64 are 23 times larger than those of PSR J1435–6100. The recently discovered PSR J1757–5322 (Edwards & Bailes 2000) has spin parameters virtually identical to those of PSR J1435–6100 (Fig. 3) and orbital parameters also similar to those of PSR B0655+64. The reason behind such contrasting sets of parameters between PSRs J1435–6100/J1757–5322 and B0655+64 is a puzzle.

3.2. *The scale-height of IMBPs and LMBPs*

The preceding discussion suggests that classifying pulsars by present-day companion mass alone may not be particularly useful. We therefore define IMBPs as objects that once had intermediate-mass donor stars. While this is a model-dependent definition, operationally it applies to pulsar systems with $10 \lesssim P \lesssim 200$ ms and $e \lesssim 0.01$. Among these systems most, but not all (e.g., PSR J1232–6501), have $m_2 \gtrsim 0.4\,M_\odot$, and $0.5 \lesssim P_b \lesssim 15$ d.

It is notable that seven of the 12 presently known IMBPs (squares in Fig. 3) have been discovered in recent low- or intermediate-latitude surveys (this *Letter* and Edwards & Bailes 2000). This is despite the greater effective volume searched with at least comparable sensitivity to pulsars with $P \gtrsim 10$ ms in some 'all-sky' surveys (e.g., Camilo, Nice, & Taylor 1996; Lyne et al. 1998). We now address this curiosity.

The median distance perpendicular from the Galactic plane for 23 known LMBPs is $|z|_\mathrm{m}$ = 0.4 kpc, and three systems have $|z| > 1.8$ kpc (Camilo 1999). For the group of 12 IMBPs, $|z|_\mathrm{m}$ = 0.2 kpc and the largest distance is $|z|$ = 0.5 kpc (Camilo 1999; Edwards & Bailes 2000; this *Letter*). Despite selection effects affecting these determinations for both populations, it appears that IMBPs have a smaller scale-height than LMBPs. The maximum perpendicular distance that a pulsar born near the plane can reach is approximately proportional to the square of its initial perpendicular velocity. A scale-height for IMBPs that may be a factor of 2–4 smaller than for LMBPs requires a velocity for IMBPs a factor of $\lesssim 2$ smaller than for LMBPs. This is plausible, considering that a typical LMBP progenitor is a $1+1.3\,M_\odot$ system while an IMBP may descend from a $4+1.3\,M_\odot$ system. In summary, the recent flurry of IMBP discoveries may be due simply to the fact that recent efforts are surveying with significant sensitivity where IMBPs tend to reside — along the Galactic plane. Similar distributions apply to X-ray binaries: HMXBs have smaller average velocity and scale-height than LMXBs (van Paradijs & McClintock 1995).

The newly discovered IMBPs are distant objects ($3 \lesssim d \lesssim 10$ kpc), and were detected because they are relatively luminous pulsars ($2 \lesssim L_{1400} \lesssim 30$ mJy kpc^2; Table 1)[11]. Therefore they need not contribute greatly to the overall population of binary pulsars in the Galaxy. However, in order to determine conclusively the scale-height of IMBPs, and their incidence among binary pulsars, it is necessary to perform careful modeling of the recent high-frequency surveys, and to measure proper motions where possible.

We are grateful to T. Tauris for many enlightening discussions, and thank R. Bhat, P. Freire, G. Hobbs, M. Kramer, D. Kubik, D. Lorimer, M. McLaughlin, and D. Morris for assistance with observations. The Parkes radio telescope is part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the US National Science Foundation (NSF). F. Camilo is supported by NASA grant NAG 5-3229. IHS received support from a Natural Sciences and Engineering Research Council of Canada (NSERC) postdoctoral fellowship. VMK was supported in part by an Alfred P. Sloan Research Fellowship, NSF Career Award (AST-9875897), and NSERC grant RGPIN 228738-00.

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[11]For typical spectral indices, these would correspond to luminosities at 400 MHz about 10 times greater, $20 \lesssim L_{400} \lesssim 300$ mJy kpc^2. For comparison, a tabulation of 21 millisecond pulsars at $d \lesssim 1.5$ kpc has median L_{400} = 10 mJy kpc^2 and only one with $L_{400} > 20$ mJy kpc^2 (Lorimer 2000).

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TABLE 1
PARAMETERS FOR FIVE BINARY PULSARS

	PSR J1232–6501	PSR J1435–6100	PSR J1454–5846	PSR J1810–2005	PSR J1904+0412
R. A. (J2000)	12 32 17.840(5)	14 35 20.2765(4)	14 54 10.908(2)	18 10 58.988(2)	19 04 31.382(4)
Decl. (J2000)	–65 01 03.33(4)	–61 00 57.956(6)	–58 46 34.74(3)	–20 05 08.3(6)	+04 12 05.9(1)
Period, P (ms)	88.2819082341(3)	9.347972210248(6)	45.24877299802(9)	32.82224432571(9)	71.0948973807(3)
Period derivative, $\dot{P}$	$8.1(2)\times10^{-19}$	$2.45(4)\times10^{-20}$	$8.16(7)\times10^{-19}$	$1.51(7)\times10^{-19}$	$1.1(3)\times10^{-19}$
Epoch (MJD)	51270.0	51270.0	51300.0	51200.0	51450.0
Orbital period, P_b (days)	1.86327241(8)	1.354885217(2)	12.4230655(2)	15.0120197(9)	14.934263(2)
Projected semi-major axis, x (l-s)	1.61402(6)	6.184023(4)	26.52890(4)	11.97791(8)	9.6348(1)
Eccentricity, e	0.00011(8)	0.000010(2)	0.001898(3)	0.000025(13)	0.00022(2)
Time of ascending node, $T_{\rm asc}$ (MJD)[a]	51269.98417(2)	51270.6084449(5)	51303.833(4)	51198.92979(2)	51449.45(25)
Longitude of periastron, ω (deg)	129(45)	10(6)	310.1(1)	159(30)	350(6)
Span of timing data (MJD)	50940–51856	50939–51856	50981–51856	50757–51817	51089–51865
Weighted rms timing residual (μs)	200	14	100	430	240
Dispersion measure, DM (cm^{-3} pc)	239.4(5)	113.7(6)	116.0(2)	240.2(3)	185.9(7)
Flux density at 1400 MHz, S_{1400} (mJy)	0.3	0.2	0.2	1.1	0.3
Derived parameters[b]					
Galactic longitude, l (deg)	300.9	315.2	318.3	10.5	38.0
Galactic latitude, b (deg)	–2.2	–0.6	0.4	–0.6	–1.1
Surface magnetic field strength, B (10^8 G)	90	5	60	20	30
Characteristic age, $\tau_{\rm c}$ (10^9 yr)	2	6	0.9	3	11
Mass function, f_1 (M$_\odot$)	0.0013	0.1383	0.1299	0.0082	0.0043
Companion mass, m_2 (M$_\odot$)	>0.14	>0.90	>0.87	>0.28	>0.22
Distance, d (kpc)	10	3.3	3.3	4.0	4.0
Distance from Galactic plane, $\|z\|$ (kpc)	0.4	0.03	0.02	0.04	0.08
Radio luminosity, L_{1400} (mJy kpc^2)	30	2	2	18	5

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Figures in parentheses are twice the nominal TEMPO uncertainties in the least-significant digits quoted, obtained after scaling TOA uncertainties to ensure $\chi^2_\nu = 1$.

[a]Due to the large covariance between ω and time of periastron (T_0) in standard TEMPO fits for pulsars with $e \ll 1$, the solutions for PSRs J1232–6501, J1435–6100, and J1810–2005 were obtained using the ELL1 model, where $T_{\rm asc}(\omega \equiv 0)$ and $(e\cos\omega, e\sin\omega)$ are fit instead (Lange et al. 2001). In these cases e and ω (as well as T_0) can be derived. For the other two pulsars we used the standard (BT) binary model that fits for e, ω, and T_0 — which is listed instead of $T_{\rm asc}$.

[b]The following formulae are used to derive some parameters: $B = 3.2\times10^{19}(P\dot{P})^{1/2}$ G; $\tau_{\rm c} = P/(2\dot{P})$; and $f_1 = x^3(2\pi/P_b)^2T_\odot^{-1} = (m_2\sin i)^3/(m_1+m_2)^2$, where $T_\odot \equiv GM_\odot/c^3 = 4.925\,\mu$s, m_1 and m_2 are the pulsar and companion masses, respectively, and i is the orbital inclination angle. m_2 is obtained from the mass function, with $m_1 = 1.35\,{\rm M}_\odot$ (Thorsett & Chakrabarty 1999) and $i < 90^\circ$. The distances are calculated from the DMs with the Taylor & Cordes (1993) free-electron distribution model; $|z| = d\sin|b|$; and $L_{1400} = S_{1400}d^2$.